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Evaluation of R&D investments in wind power in Korea using real option

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ABSTRACT

In recent years, many countries put an emphasis on the development and deployment of renewable energy to cope with the global environmental crisis such as depletion of fossil energy, climate convention to control emissions of greenhouse gases. Among the various new and renewable energy sources, the Korean government selected wind power energy as one of the core areas for R&D investments. In this paper, we evaluate the economic value of the investment in wind power energy R&D in Korea and optimal deployment timing of wind power technology by using the real option approach. The real option model adopted in this paper assumes that a decision maker has a compound option to abandon, deployment, or continue the R&D. As a result by using empirical data of Korea, it is found that there exists a considerable amount of positive economic value of investments in wind power energy R&D.

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Contents

1. Introduction

The accelerating depletion of fossil fuel resources and volatility of oil prices, coupled with regulatory responses to environmental changes such as the Climate Change Convention for reduction of greenhouse gas emissions, has made clear the importance of utilizing renewable sources of energy such as wind, photovoltaic, thermal heat, and biological organisms. In recent years, sources of renewable energy have come to be perceived no longer as simple alternatives to fossil fuels, but rather as basic and indispensable sources of energy that provide a solution to the energy crisis the planet is facing.

Developing and commercializing new and renewable energy sources requires huge initial investments. Nevertheless, developed

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Table 1
Trend of annual R&D investment in renewable energy technology development projects in Korea (1988–2011) (Unit: Billion KRW).

Year	Total renewable energy			Wind power		
	Public	Private	Total	Public	Private	Total
~2002	152	98	250	14	9	23
2003	33	18	51	4	2	6
2004	59	32	91	8	2	10
2005	79	43	122	11	4	15
2006	116	77	193	17	6	23
2007	121	93	214	17	10	27
2008	195	173	368	18	9	27
2009	206	137	343	38	33	71
2010	240	129	369	41	32	73
2011	243	214	457	42	33	75
Total	1445	1012	2456	209	140	349

countries are aggressively investing in related R&D programs and undertaking policies to expand the use of renewable energy sources. This is also the case in Korea, where there is a keen awareness of the critical importance of new and renewable energy sources. Indeed, the Korean government has had a 'basic plan for technological development, utilization and deployment of renewable energy' in place since the late 1990s. In the process of designing and implementing the basic plan, the Korean government came to understand that continuous investment in R&D is indispensable for developing advanced technologies and facilitating the commercialization of renewable energy technology. Indeed, funding by both the public and private sectors of Korea towards R&D programs is continuously increasing as shown in Table 1.

Among the various new and renewable energy sources, the Korean government selected wind, photovoltaic, and fuel cell based energy as the three core areas for R&D investments. In particular, wind power has attracted increasing attention in Korea not only because it is the most technically advanced and economical source of renewable energy, but also because numerous places in Korea experience heavy winds on a year-round basis. Starting with the wind farm on Jeju Island (9795 kW capacity) constructed as a governmental pilot project in 1997, 17 wind farms are now in operation in Korea. While a total of 272 wind-power generation systems were installed as of 2012 with a total capacity of 448.35 MW [1], Korea still has a low level of wind power deployment compared with that of the US (60.0 GW), Germany (31.3 GW), China (75.3 GW), and Spain (22.8 GW) [2]. Hence more aggressive investment in wind power technology is required in Korea.

Indeed, as the scale of R&D investment in wind power in Korea increases, the demand for studies to analyze and justify the efficiency of investments has increased. Furthermore, since R&D investments are considered high risk and include various kinds of options in the decision making process such as delay, abandonment, and expansion, it is important to consider uncertainty and these options simultaneously when evaluating economic values and deciding when to deploy the results of R&D for wind power energy. However, there is a paucity of empirical research on economic evaluation of wind power energy R&D in Korea performed using real option analysis.

The aim of this study was to provide an empirical calculation of economic values of R&D investment in wind power energy technology of Korea based on a real options model taking into consideration the uncertainty of fossil fuel prices. To quantify the economic values of managerial decision options with respect to wind power energy R&D, we identified optimal decision-making choices and timing of options under various situations of uncertainty. Specifically, we used empirical data and government plans to evaluate the economic values of wind power energy R&D using both a traditional DCF model and a real options model. We performed a comparative analysis on the results obtained by both models. In addition, we derived an optimal decision path as a function of time according to energy market uncertainty by analyzing a binomial lattice model in which the optimal timing of R&D and deployment were identified. Sensitivity analysis with respect to important model parameters was also performed. Finally, we present relevant policy implications based on the results obtained from this study.

The rest of this paper is organized as follows: Section 2 provides a short review of relevant literature. In Section 3, we present the two models employed in this study to evaluate wind power energy R&D. In Section 4, we briefly describe the data used in this study, describe the results of our evaluation using the two models as well as the results of the sensitivity analysis, and discuss the policy implications of these findings. Lastly, we present our conclusions in Section 5.

2. Literature review

In order to make informed decisions concerning the allocation of public funding for wind power energy R&D, the ability to accurately assess the economic effects of R&D programs is critical. Menegaki [3] reviewed the literature on valuation or evaluation of renewable energy resources and summarized existing methods of analysis. In their review study, the authors argued that it is important to consider the values of renewable energy, which are difficult to evaluate in the perspective of traditional valuation methods. Along these lines, the accuracy of discounted cash flow (DCF) analysis, a traditional method widely used for estimating the economic effects of R&D, is often called into question. Indeed, it has been pointed out that this method tends to underestimate the value of R&D activities [4,5] as well as renewable energy projects including wind power [6–8]. The consequences of inaccurate assessment of the economic effects of wind power energy R&D programs on funding prospects for related projects are bound to be negative. The main reason why the economic value of wind power energy R&D under the DCF method tends to be underestimated is that DCF analysis fails to adequately reflect the flexibility of decision-making in the face of uncertainty in the energy market, and more particularly, uncertainty linked to fluctuations in the price of fossil fuels. Thus, there is a need for more accurate methods for estimating the economic effects of wind power energy R&D that take into account the flexibility of decision-making. Indeed, flexibility of decision-making is an important variable to consider, because it allows organizations and governments to respond promptly to market uncertainties and rapidly commercialize new technologies.

Several attempts have been made in recent years to employ a technique known as *real option analysis* for economic valuation of R&D programs for renewable sources of energy, including wind power. In an early application of real option analysis used to evaluate the benefits of R&D with respect to new and renewable energy sources, Davis and Owens [6] estimated the value of renewable energy generation technologies using a continuous real option model, taking into consideration the price uncertainty of fossil fuels. In their study, which was directed at quantifying the benefits of federal renewable energy generation R&D programs funded by the US government, Davis and Owens [6] stressed that the main goals of federal non-hydro renewable electric R&D programs are to facilitate the development of stable energy supply technologies. Similarly, Siddiqui et al. [7] assessed the economic value of renewable electric power R&D programs using a method

Table 2
Summary of real options literature.

Authors	Energy source	Uncertainty	Model	Year	Ref.
Davis et al.	Renewable energy	Electricity annual rate of cost reduction/increase	PDE	2003	[6]
Siddigui et al.	Renewable energy	Fossil fuel price	Tree	2007	[7]
Lee et al.	Renewable energy	Non-renewable energy cost	Tree	2010	[10]
Martinez-Cesena et al.	Hydropower	Electricity price	Tree, Sim	2011	[11]
Fleten et al.	Wind energy	Electricity price	PDE	2004	[13]
Zhou et al.	Wind energy	Electricity price	Sim	2007	[14]
Munoz et al.	Wind energy	Electricity price	Tree, Sim	2009	[15]
Marinez-Cesena et al.	Wind energy	Wind resource	Tree, Sim	2012	[16]
Lee	Wind energy	WTI price	PDE	2011	[17]
Lee et al.	Wind energy	Non-renewable energy price	Tree	2011	[18]
Yoon	Combined heat and power plant	Oil price	Tree	2001	[19]
Lee et al.	Wind energy	Electricity price	PDE	2012	[20]

PDE: partial differential equation and Sim: Simulation.

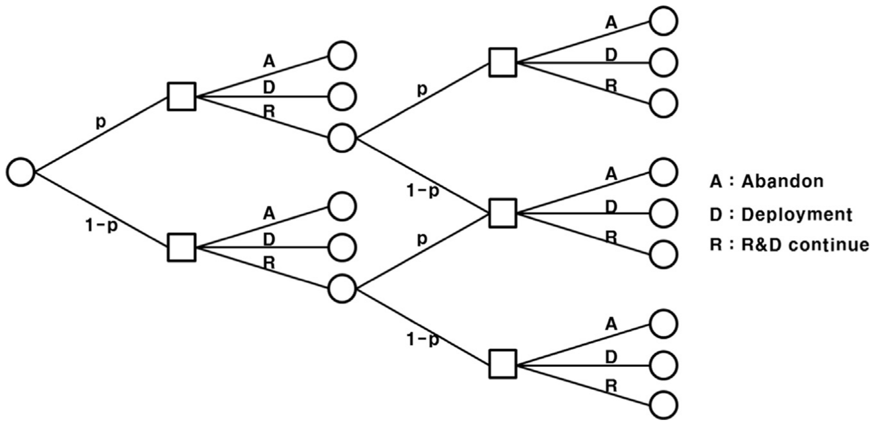

Fig. 1. Decision tree.

inspired by Brennan and Schwartz [9] for valuing copper mines. Specifically, Siddiqui et al. [7] created options lattices for an empirical analysis using a binomial option-pricing model and compared their results with those obtained by Davis and Owens [6]. Lee and Shih [10] applied real option analysis similar to the model used by Siddiqui et al. [7] to evaluate renewable energy policy evaluations in Taiwan; however, they focused on overall policy factors rather than the specific effects of R&D. Recently Martinez-Cesena and Mutale [11] proposed a more advanced real option methodology which combines optimization model with real option for evaluation of renewable energy generation projects planning.

With respect to wind power, Olivera and Fernandes [12] reviewed existing studies regarding economic evaluation of wind energy projects focusing on an optimization model. Among several attempts to apply real option analysis to investments in wind energy, Fleten and Maribu [13] were the first to use it to evaluate investment timing and capacity choice problems for small wind power projects taking into consideration the variability of wind speed and demand. Later, Zhou et al. [14] performed real option analysis to evaluate wind power generation asset investment, in which a mean reversion process was employed to describe the characteristics of electricity prices taking into account fluctuations, uncertainty, and periodicity. Munoz et al. [15] developed a decision-making model for wind energy investments taking into consideration the uncertainty of wind production and electricity prices based on real option analysis to specifically determine the probabilities one should invest, wait, or abandon a given project. Similarly, Martinez-Cesena and Mutale [16] proposed a real option analysis framework to incorporate wind resource assessment uncertainty in the planning and design process of wind power projects. However all of these approaches deal with investment in wind power generation facilities rather than R&D of wind power technology. Lee [17] and Lee and Shih [10,18] presented a series of empirical works of applying real option to the evaluation of wind power energy in Taiwan.

Among Korean researchers who have looked at increasing uncertainty within the energy market resulting from structural reform of the industry and trends toward market liberalization, Yoon [19] stated that the real option analysis approach may be an effective technique for evaluating the economic efficiency of investments in new and renewable energy R&D programs. Recently, Lee et al. [20] performed an economic evaluation of offshore wind power demonstration project which was outlined in the 'South-western Offshore Wind Plan' published in 2011 by using real option method. Although Lee et al. [20] is a pioneering empirical analysis that applies real option model to wind power, it does not address R&D but only wind farm project. Table 2 summarizes the relevant literature using real option approach.

3. Model

3.1. Discounted cash flow (DCF) model

The most commonly employed method to estimate the economic value of new and renewable energy R&D is the discount cash flow (DCF) model. DCF models estimate the investment value of R&D programs by calculating its net present value (NPV) and applying a discount rate on the forecasted cash flow at a future

point in time. DCF models are also widely used for investment value analysis of general investment assets.

In order to obtain the NPV of a wind power technology using the DCF model, it is first necessary to predict the future cash flow generated from the technology. The unit benefit is defined as the generation cost reduction from fossil fuel energy to wind power energy. NPV is the present value of total power generation cost reduction resulting from R&D for wind power less the expenditure on R&D. The formula for calculating NPV is as follows:

$$NPV = \sum_{t=0}^{n} \delta^t [(P_{NRE}(t) - P_{WP}(t))WP(t) - C(t)] \quad (1)$$

where NPV is the net present value, $P_{NRE}(t)$ is the unit cost of fossil fuel power generation at the time period t, $P_{WP}(t)$ is the unit cost of wind power generation at the time period t, $WP(t)$ is the amount of wind power generation during the time period t, $C(t)$ is the R&D expenditure for wind power and δ is the discount factor $(\delta = (1/1+\gamma),$ where γ is the risk $-$ free interest rate)

3.2. Real option model

The real option model employed in this study was based on the model presented by Siddiqui et al. [7]. We assumed that there were three decision-making options regarding R&D activities of wind power technology, namely, to continue R&D, deploy the results of R&D, or abandon R&D. In the first case, if oil prices continue to increase and the effect of R&D to reduce the cost of wind power is expected to be successful, then the decision maker would want to continue funding R&D. For the second option involving R&D deployment, if the results of R&D have reached a satisfactory outcome and the generation cost of wind power is competitive with that of fossil fuel energy, then commercialization of R&D should be considered. Abandonment is the third option, and can be chosen if there is a reason to stop the on-going development of projects. In our study, we assumed that if R&D results were commercially deployed or once research was abandoned, the project could no longer be resumed. For convenience of analysis, we did not take into consideration technology risks. In other words, we assumed that all R&D projects attained their target outcome, disregarding the possibility of failure in technology development.

The unit cost of fossil fuel power generation was assumed to follow geometric Brownian motion (GBM). $P_{NRE}(t,i)$ corresponds to the unit price of fossil fuel power generation during the time period t, while i is the number of increases in unit cost during the period t. The initial unit cost of fossil fuel power generation is expressed as $P_{NRE}(0,0)$, where the unit cost can have two probability values, namely, the probability p that the unit cost will increases, which is calculated by multiplying the initial price by u, and thus $P_{NRE}(1,1) = uP_{NRE}(0,0)$; and the probability $1-p$ that the unit cost will decrease, which is calculated by multiplying the initial price by d, and thus $P_{NRE}(1,0) = dP_{NRE}(0,0)$. We let γ be the risk-free interest rate and σ be the past volatility of the unit ;cost of fossil fuel power generation, such that $u = e^{\sigma}$, $d = 1/u = e^{-\sigma}$, $p = (e^{\gamma} - d)/(u-d)$. Fig. 1 illustrates the decision tree of the options described above with respect to the two events and the rise and fall of fossil fuel energy costs.

As shown in Fig. 1, if a new technology resulting from a wind power energy R&D project has not been deployed, there are three options available at any given time t. Thus, the final option values

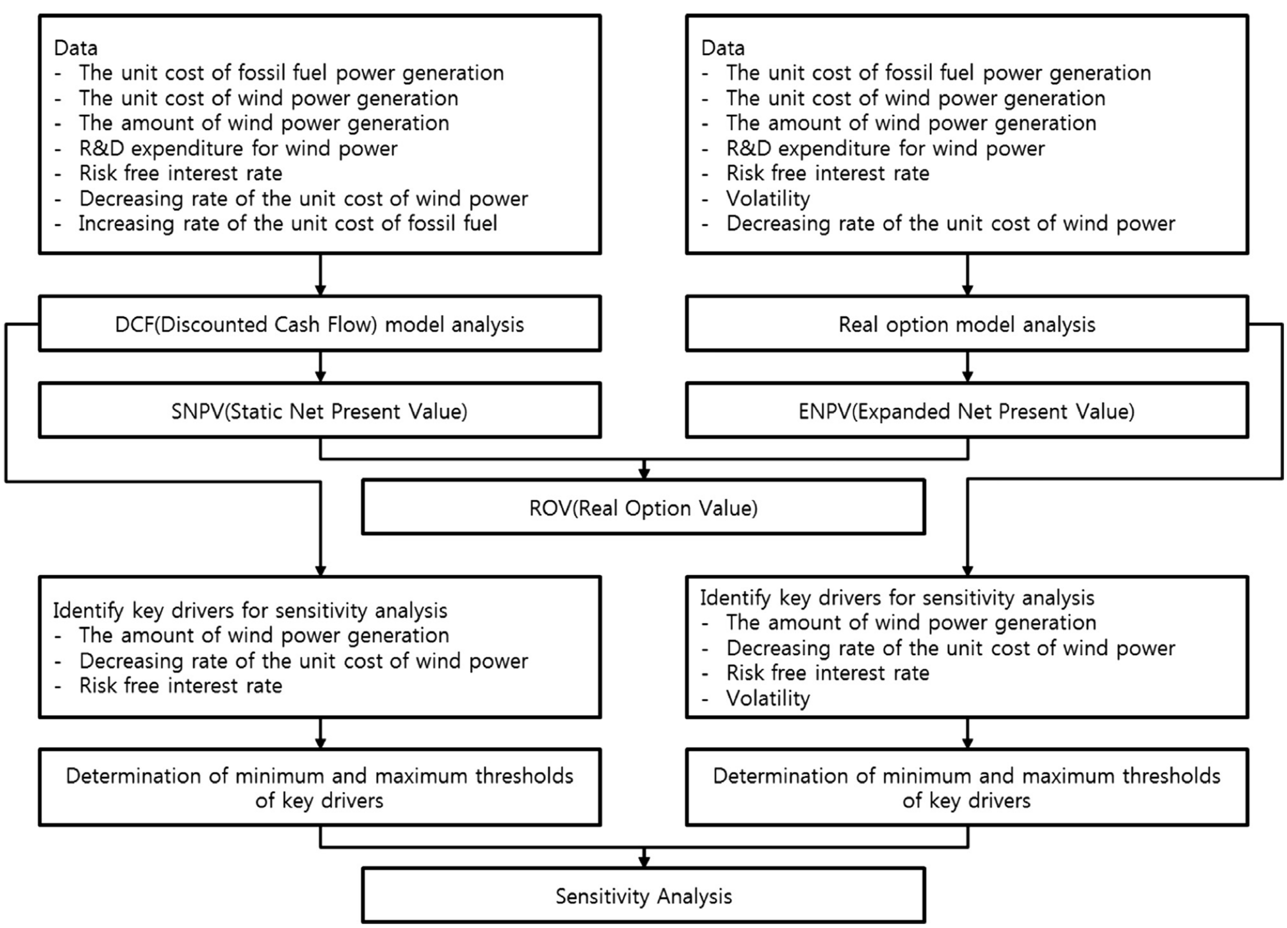

Fig. 2. Procedure of analysis.

in this study can be calculated using

$$V(t,i,r)=\max\begin{bmatrix}-A;\\ \Pi(t,\ i,\ r,\ t)-D;\\ -C(t)-M+\delta(pV(t+1,\ i+1,\ r+1)+(1-p)V(t+1,\ i,\ r+1)\end{bmatrix} \tag{2}$$

The first term, $-A$, represents the loss incurred by abandoning an R&D project. The amount of loss, $-A$, is assumed to be equal to the total investment into the project. The second term, $\Pi(t,\ i,\ r,\ t)-D$, is the net profit expected to be generated at any given time t if the results from the R&D project are commercially deployed. Here, D denotes the cost of commercial applications of R&D results, including testing, prototyping, and marketing, etc. The expected profit to be generated from the deployment of a technology resulting from an R&D project for wind power is realized in the form of cost savings made by consumers using wind power energy at a price cheaper than that of fossil fuel energy, which can be expressed using formula as follows:

$$\Pi(t,i,r,j)=(P_{NRE}(t,i)-P_{WP}(t,r))WP(j,t)-M+\delta[p\Pi(t+1,\ i+1,\ r,\ j) \\ +(1-p)\Pi(t+1,\ i,\ r,\ j)] \tag{3}$$

In Eq. (3), the term $(P_{NRE}(t,i)-P_{WP}(t,r))WP(j,t)-M$ corresponds to the amount of the current cost savings, while the rest corresponds to the amount equal to the future cost savings. Specifically, $WP(j,t)$ stand for the amount of power generated from wind power energy sources at the time period t if the wind power technology developed from an R&D program is deployed during the time period j. Meanwhile $P_{WP}(t,r)$ represents the unit cost of wind power generation during the time period t, where r is the number R&D projects undertaken until deployment and M is the O&M cost incurred after industrial application of the new wind power technology. The final term is the sum of the costs incurred during R&D and O&M if project R&D continues combined with the value of the profits expected to be realized in the future. Therefore, formula (2) compares cash flow under the three options available during an R&D project, through repeated rounds of comparison, to discover the largest value. Thus, the final option value, which can be obtained by backward induction, can be expressed as

$$V(0,0,0)=\max\begin{bmatrix}-A;\\ (P_{NRE}(0,0)-P_{WP}(0,0))WP(0,0)-M+\delta[p\Pi(1,1,\ 0,\ 0)+(1-p)\Pi(1,\ 0,\ 0,\ 0)]-D;\\ -C(0)-M+\delta(pV(1,\ 1,\ 1)+(1-p)V(1,\ 0,\ 1)\end{bmatrix} \tag{4}$$

In addition, we performed the sensitivity analysis for various variables in order to supplement the results of analysis based on the above two models. For sensitivity analysis, variables of which values are likely to affect the economic values of R&D for wind power energy are selected. Next we re-calculate the NPV and the expanded NPV with respect to the various values of each of selected variables by changing it from 10% to 200% of the reference value with others remain unchanged. By doing so, we can examine how much and to which direction certain variable would affect the economic values of R&D for wind power energy.

Fig. 2 illustrates the procedure of analysis stage by stage including sensitivity analysis.

4. Analysis

4.1. Data

The input parameters used in this paper are summarized in Table 3.

In general, the unit cost of non-renewably generated electricity can be estimated using the actual data of capital cost, fuel cost and operating cost. However those data were not accessible because they were regarded as internal and closed data in Korean companies. Furthermore it is almost impossible to estimate this cost as a single representative value because it could be measured differently with respect to energy sources and power plants. For these reasons, we estimated the unit cost of non-renewably generated electricity based on the making-up price of each non-renewable energy source which is reported officially. It should be noted that this is the second-best method because there could be a little difference between the unit cost and the making-up price that includes not only the cost but also profits.

The unit cost of non-renewably generated electricity was calculated as the weighted average of the making-up price of each energy source except for renewable energy sources. The weights of energy sources were assumed to be the relative proportion of each energy source to the total generation of electricity. The raw data used in our calculations were obtained from Electric Power Statistics Information System (EPSIS) provided by the non-profit organization Korea Power Exchange (KPX) [22]. Table 4 shows the data and procedure of unit cost calculation. As a result, the unit generation cost of non-renewable energy was set to 89.60KRW in 2012.

Table 3
Input parameters.

Variable	Description	Unit	High	Middle	Low
$P_{NRE}(0,\ 0)$	Initial cost of non-renewable energy generation	KRW/KWh	89.60	89.60	89.60
$P_{WP}(0,\ 0)$	Initial cost of wind power generation	KRW/KWh	98.96	98.96	98.96
$P_{WP}(t,\ 0)$	Cost of wind power generation at t without R&D	KRW/KWh	98.96	98.96	98.96
$P_{WP}(t,\ t)$	Cost of wind power generation at t with R&D	KRW/KWh	Fig.3	Fig.3	Fig.3
N	Number of time periods	Years	18	18	18
γ	Risk-free interest rate	%	3.30	3.30	3.30
δ	Discount factor		0.97	0.97	0.97
σ	Volatility	%	34.17	13.52	6.72
p	Probability of a price increase in each period		0.46	0.59	0.73
$C(t)$	Annual R&D expenditure during t	KRW	Fig. 4	Fig. 4	Fig. 4
A	Abandonment cost	KRW	Fig. 4	Fig. 4	Fig. 4
D	Deployment cost	KRW	0	0	0
$WP(j,\ t)$	Amount of power generated from wind power at t when deployed at j	GWh	Fig. 5	Fig. 5	Fig. 5

The unit cost of wind power generation was set to 98.96KRW based on 2012 data and we assumed that the R&D projects currently underway would provide an average annual decrease in unit cost of 2% as currently forecasted by the Korean government [21]. In order to forecast the future unit cost of non-renewable energy generation, we assumed an average annual rate of increase of 5.86%, which was calculated using the compound annual growth rate (CAGR) of the unit cost of non-renewable energy generation from 2001 to 2012. Fig. 3 compares the trends for unit generation costs of non-renewable energy and wind power.

Taking into consideration data availability and the goals set forth by the Korean renewable energy policy, the time period evaluated in this study was set as 18 years, from 2012 to 2030. The risk-free interest rate, γ, was set to 3.30%, which is the interest rate on 91-day certificate of deposits (CDs) in 2012, which indicates the high liquidity of short-term bonds in Korea. The future plan of annual R&D investment for wind power energy was publicized in

Table 4
Unit cost of non-renewable energy generation.

Energy source	Generation (GWh)	Proportion (A) (%)	Making-up price (B) (KRW/KWh)	Weighted sum ($C=A\times B$) (KRW/KWh)
General hydropower[a]	3348	0.72	180.86	1.31
Pumped-storage hydropower[a]	3634	0.79	213.93	1.68
Anthracite	8020	1.73	103.79	1.80
Coal	184,603	39.88	66.25	26.42
Petroleum	14,524	3.14	252.96	7.94
LNG	105,177	22.72	168.10	38.20
Nuclear	143,548	31.01	39.52	12.26
Sum	462,854	100.00		89.60

[a] Note that the hydropower shown in Table 4 implies large-scale hydroelectric power generation. Because only small-scale hydroelectric power generation under 10 MW is categorized into renewable energy source in Korea, large-scale hydroelectric power generation is included in non-renewable energy source [25].

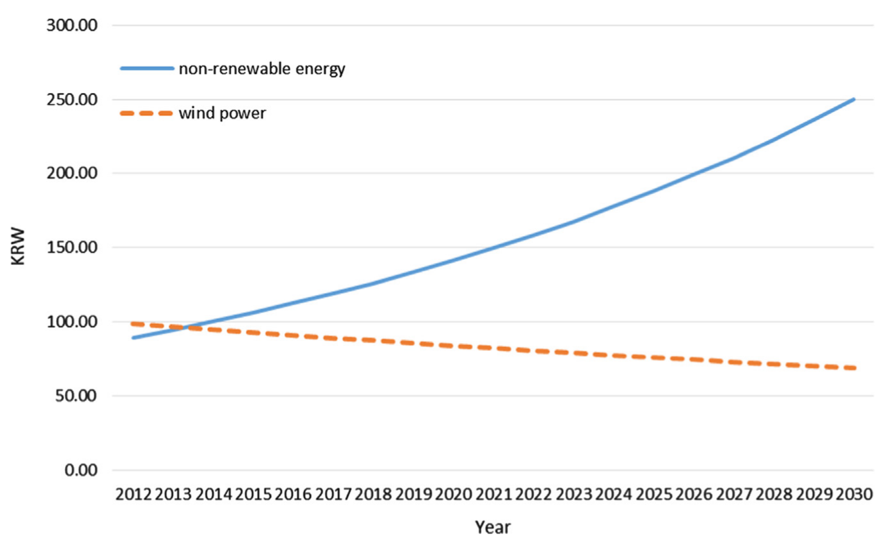

Fig. 3. Forecasting the trends of unit cost of generation (Unit: KRW).

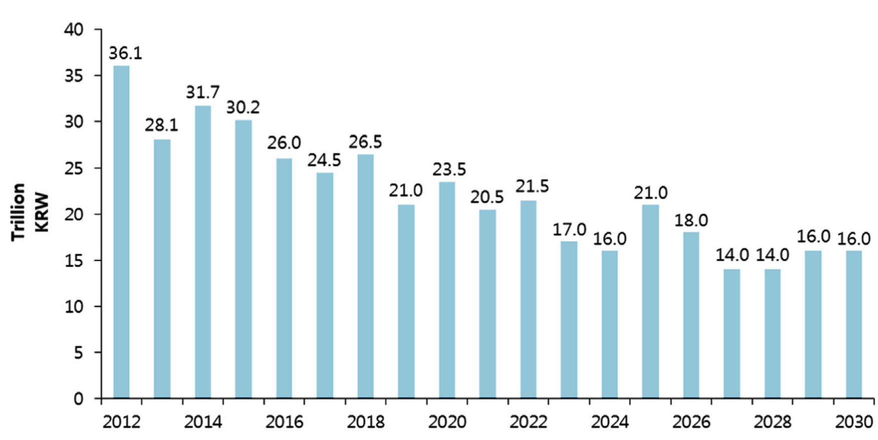

Fig. 4. Future annual R&D investment of wind power (Unit: Trillion KRW).

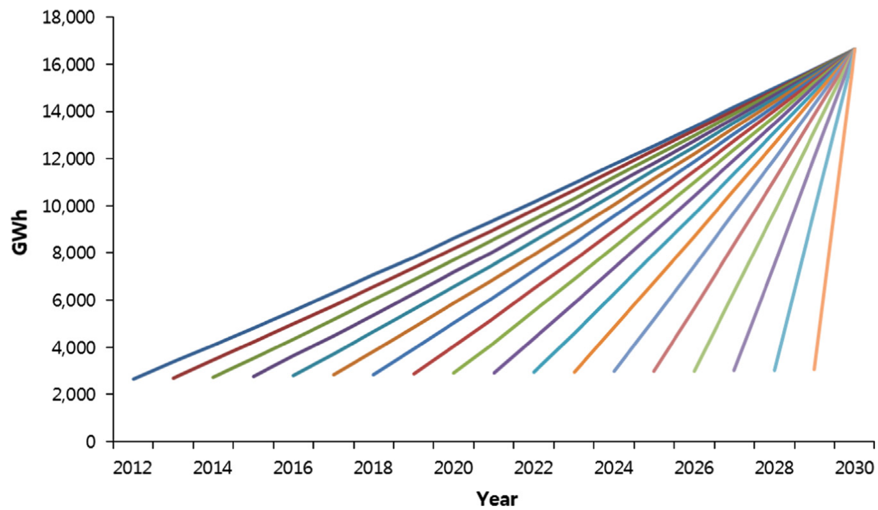

Fig. 5. Amounts of wind power generation with respect to deployment timing (Unit: GWh).

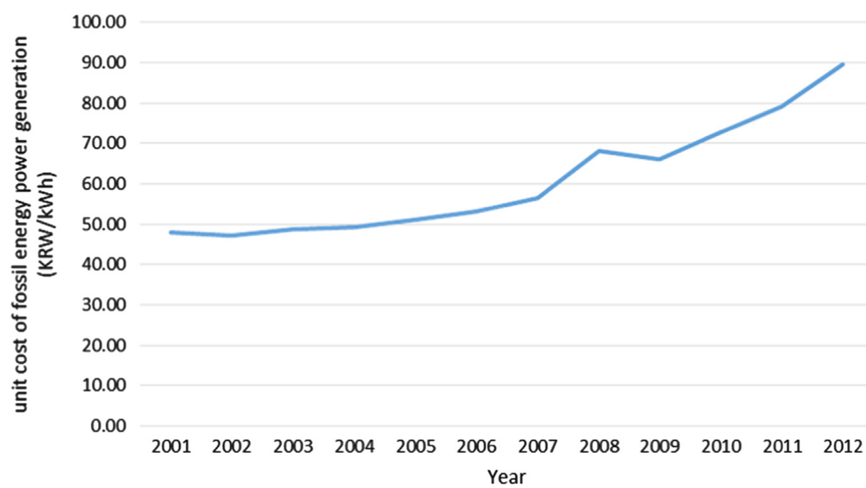

Fig. 6. Trend of unit cost of fossil fuel energy in Korea.

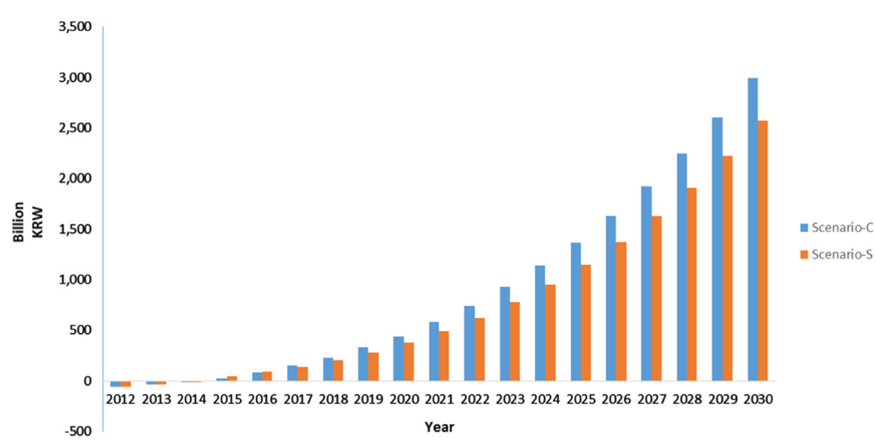

Fig. 7. Forecasted cash flows of both scenarios (Unit: Billion KRW).

the 'New and Renewable Energy R&D Strategy 2030' [23] and was as the data for annual R&D expenditure, $C(t)$, as shown in Fig. 4.

The amount of power generated from wind farms was obtained by calculating the wind power share of the total power generation after deployment of energy technologies developed through the R&D projects currently underway. The total annual power generation was forecasted by the regression analysis using not only the past data but also the official forecasting results given by third basic plan on electricity demand and supply of the Ministry of Industry and Energy [26]. As a result, the total power generation

level in 2030 is forecasted as 544,289 GWh. After forecasting the total annual generation level, we assumed that the share of wind power energy generation of the first year of deployment was 0.48% of the total generation of the year, which was the percentage of current wind power generation (2262.9 GWh) of the total power generation (474,216 GWh) in Korea in 2012. With respect to R&D deployment, we assumed that the policy goal of wind power generation (16,620 GWh) would be attained by 2030 and thus the percentage of power generated by wind would be 3.05%. Between the year of deployment and 2030, annual values were computed by a straight line connecting two points of 0.48–3.05% for the sake of simplicity, which assumed that the speed of attaining the goal of power generation would increase as a result of the cost competitiveness of wind power energy improving with the later timing of R&D deployment. The amount of power generated by wind power at time t when deployed at j, $WP(j,\ t)$, is indicated in Fig. 5.

Table 5
Results of NPV analysis (Unit: Billion KRW).

Scenario	NPV
Scenario-C	6708
Scenario-S	5730

4.2. Net present value analysis

While the unit cost of non-renewable power generation increased over time, the unit cost of wind power generation dropped progressively, indicating that the unit cost of non-renewable power generation in the future should be higher than the unit cost of wind power generation. In the case of Korea, assuming that the unit cost of wind power generation would fall at an average annual rate of 2%, our results indicated that the price relationship between two energy sources would be reversed by the year 2014. In other words, the grid parity of wind power energy should be reached by the year 2014.

Then is there any real evidence to support this result in Korean energy market? At first, it is witnessed that the cost of fossil fuel energy generation has been increasing in Korea except for temporary down in 2009 due to the global financial crisis shown by Fig. 6. And there is a compensation system in Korea, called Feed-in-Tariff (FIT), in which the government compensates for

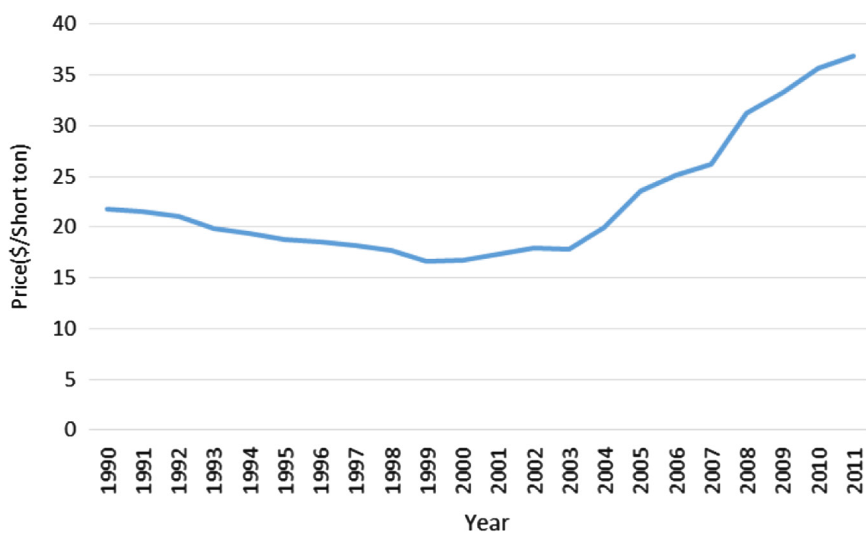

Fig. 8. Trend of the price of coal in global market (Unit: \$/short ton).

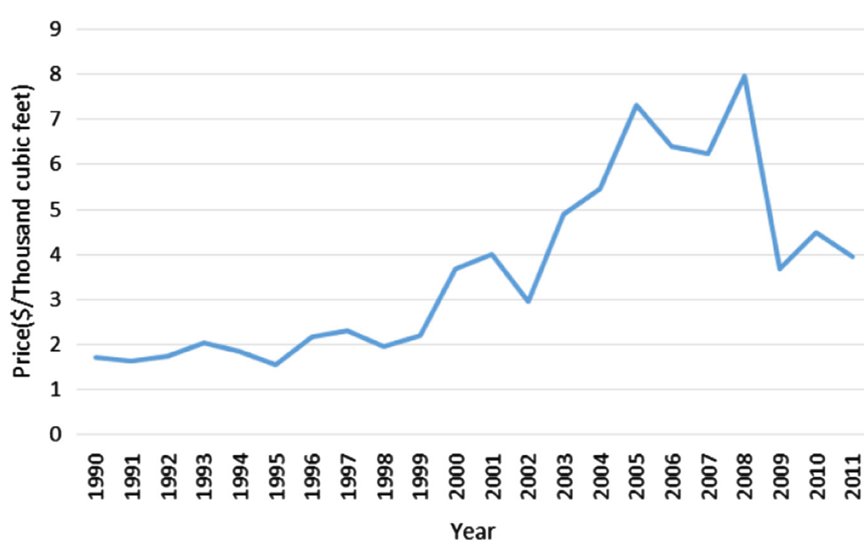

Fig. 9. Trend of the price of natural gas in global market (Unit: \$/ft^3).

differences between the electricity costs of renewable energy and fossil fuel power generation to promote the production and use of such sources. In case of wind power, it has not needed to be compensated by FIT since 2011, which implies the cost of wind power energy achieved the same level of fossil fuel power gene ration. Therefore the recent overall energy market situation of Korea might support our result that wind power energy would be competitive with non-renewable energy with the increase trend of fossil fuel energy price although the analysis could not incorporate the entire influential factors on this issue..

Once this point is reached, wind power energy will be competitive with non-renewable energy power, even without R&D projects for developing new technologies, because the unit cost of non-renewable energy power generation will continue to increase.

We employed two scenarios to reflect hypothetical situations that may arise after the unit cost relationship between non-renewable energy power and wind power is reversed, and analyzed them both using the DCF model. In scenario-S, once the unit cost of wind power becomes cheaper than that of non-renewable energy, further R&D investments for wind power technology would be stopped because the goal of R&D is attained. So under this scenario, the unit cost of wind power will be no longer decreased. On the other hand, in scenario-C, even after the unit cost of wind power reaches at the level of non-renewable energy, R&D investments for wind power technology would be continued in order to make wind power technology have market competitiveness more and more. When calculating the net present value of forecasted cash flows, a discounting rate of 7% was applied based on the guidelines published by the Ministry of Industry and Resources [24]. Fig. 7 illustrates the cash flows of the two scenarios. The net present values are given in Table 5.

As shown in Fig. 7, cash flow in both scenarios started at a negative value but became positive beginning in the year 2015, just one year after the unit cost of wind power generation became less than that of non-renewable energy. In addition, beginning in the year 2017, the cash flow of scenario-C is greater than that of scenario-S. A possible explanation for this observation was that the profits realized from the continuation of power energy R&D were greater than those invested in R&D. As a result, the NPV of scenario-C was greater than that of scenario-S by 800 billion KRW. In conclusion, based on NPV analysis, R&D for wind power is economically justifiable if it achieves a decline in unit generation cost of 2%. Furthermore, even though our data indicated that grid parity of wind power energy could be accomplished, it is still desirable to continuously invest in R&D.

Table 6
Results of real option analysis (Unit: Billion KRW).

Volatility	R&D after grid parity	ENPV	NPV	ROV
High	Continue	6417.8	6708	−290.6
	Stop		5730	688.2
Middle	Continue	4565.3	6708	−2143.1
	Stop		5730	−1164.3
Low	Continue	4178.4	6708	−2529.9
	Stop		5730	−1551.2

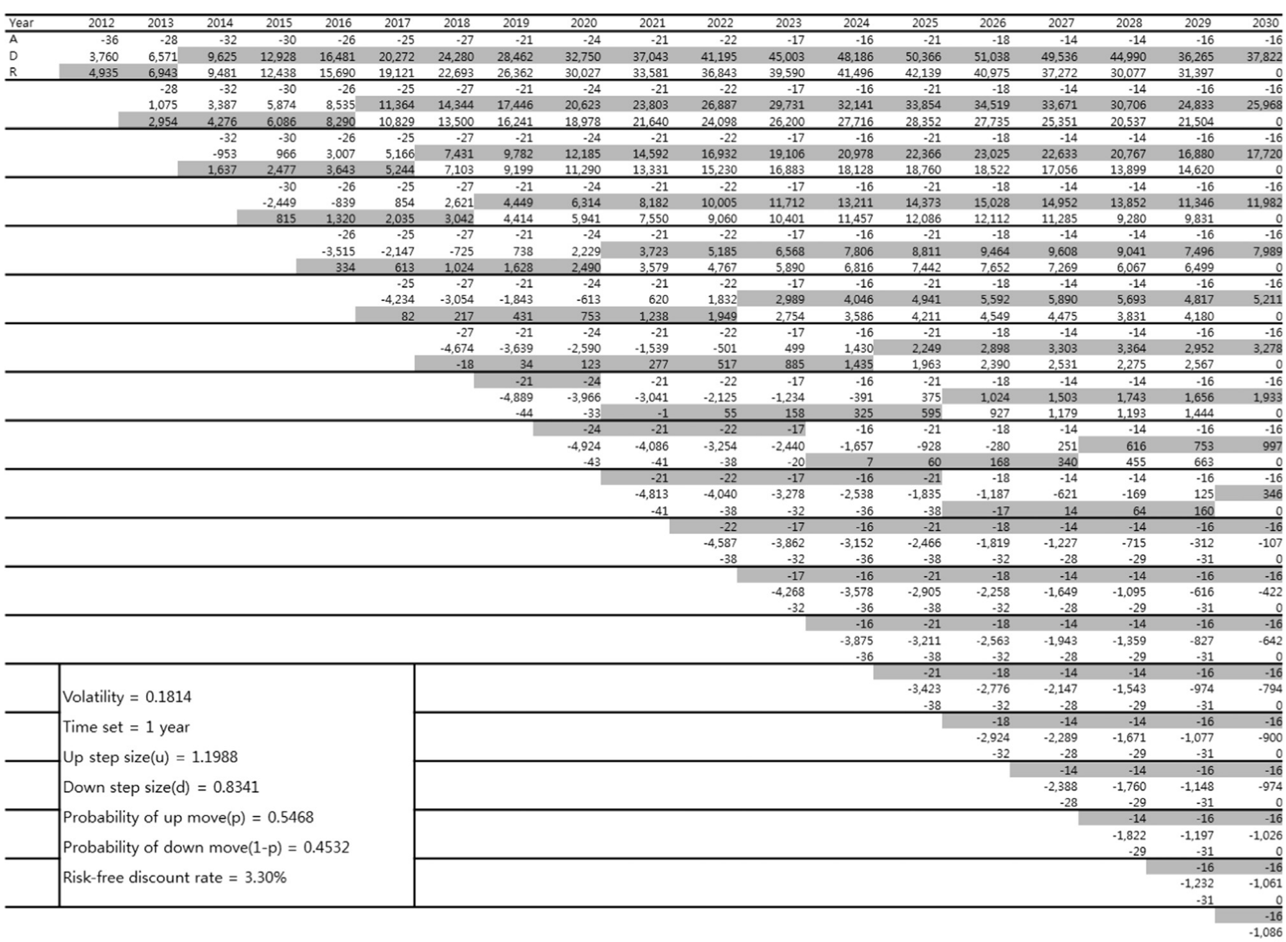

Fig. 10. Binomial lattice of option values in average volatility (Unit: Billion KRW).

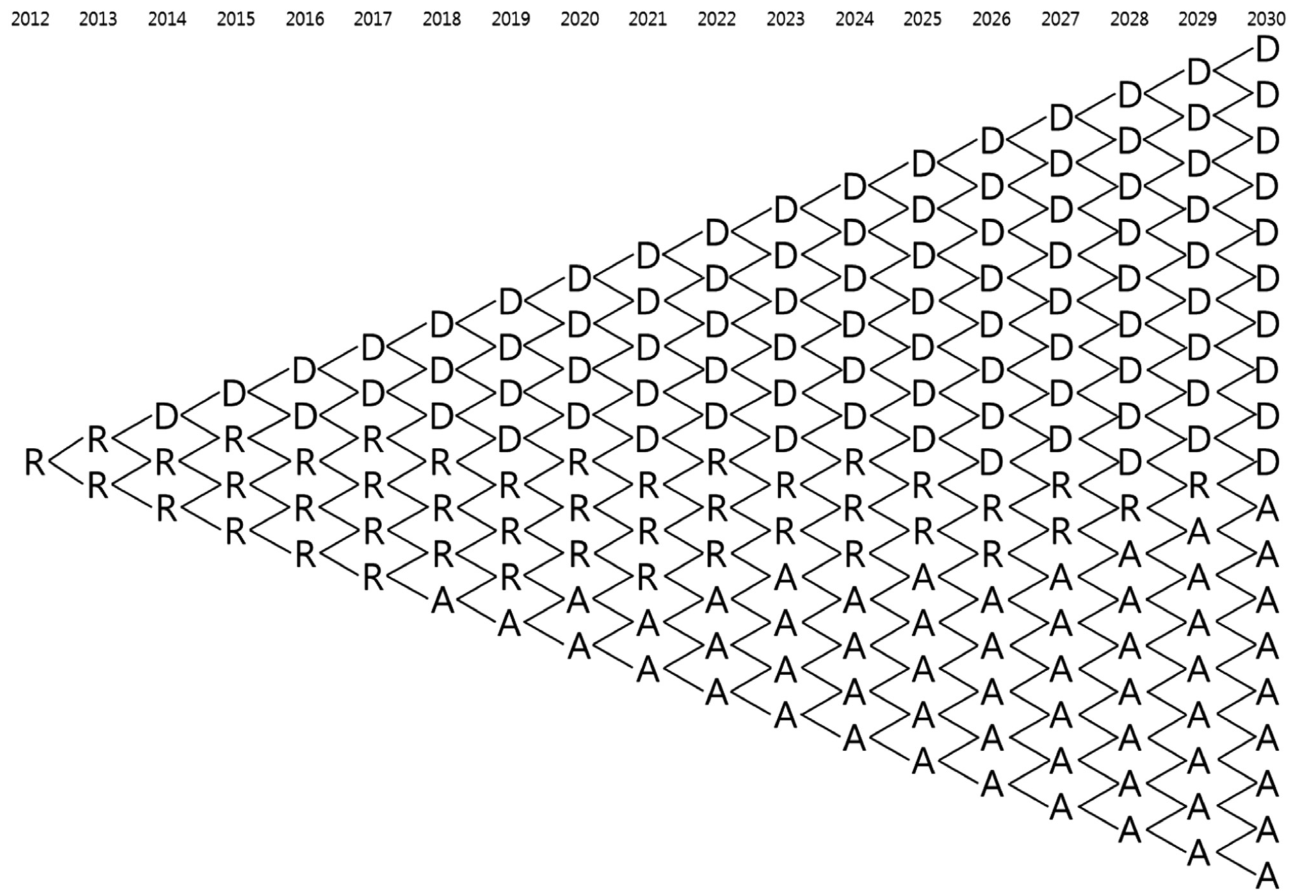

Fig. 11. Optimal decision lattice in average volatility (A: abandon, D: deploy, R: invest R&D).

4.3. Real option analysis

A key parameter in real option analysis is the volatility of the unit cost of non-renewable energy generation. In Korea, non-renewable energy consists primarily of fossil fuel sources, with the exception of some nuclear energy that contributes to the share of total generation. In our study, we selected coal and natural gas as the main sources of fossil fuel energy in Korea. Thus, the volatility of unit cost of non-renewable energy generation was assumed to be directly related to variations in the prices of coal and natural gas in the global market. Figs. 8 and 9 illustrate the trends of prices for coal and natural gas, respectively.

Because it is impossible to forecast future volatility exactly, we assumed three scenarios regarding the magnitude of volatility using the simple volatility method. In scenario-H, we used a high volatility of 34.17%, which was obtained from the prices of natural gas between 2001 and 2011. In scenario-M, a middle volatility of 13.52% was obtained from the weighted average prices of 75% coal and 25% natural gas between 2001 and 2011. In scenario-L, a low volatility of 6.72% was obtained from the prices of coal price between 2001 and 2011.

In the context of real option analysis, the term Expanded Net Present Value (ENPV) is defined as the sum of Static Net Present Value (SNPV) and Real Option Value (ROV), such that ENPV = SNPV + ROV [5]. Thus, ENPV includes the option values possessed by a given project. As described above, our model considered three options, namely, to continue R&D, to deploy the results of R&D, and to abandon R&D. Table 6 shows the results of the real option analysis according to case scenarios H, M and L.

The results of real option analysis showed that the ENPV of R&D for wind power technology ranged from 4.18 trillion KRW in the low volatility case to 6.42 trillion KRW in the high volatility case. The highest ROV was 0.69 trillion KRW, which was obtained for the scenario combination of 'high volatility' and 'stop R&D after reaching parity grid.' Thus, the value of managerial flexibility to make an optimal decision among the three given options in order to cope with energy market uncertainty at each stage was the greatest when market uncertainty was high and investments in R&D investment were discontinued after reaching grid parity with wind power energy. On the other hand, it is worthwhile to note that a negative ROV value of −2.53 trillion KRW was obtained for the scenario combination of 'low volatility' and 'continue R&D after reaching grid parity.' We interpreted this result to indicate that in markets with low uncertainty, it is more economically desirable to invest and perform R&D than to consider other options by means of managerial flexibility, even after the unit cost of wind power generation becomes cheaper than fossil fuels. This finding was somewhat unexpected, and may be the result of assuming no uncertainty for R&D.

The binomial lattices of the option values and optimal decision lattice for average volatility case are illustrated in Figs. 10 and 11.

In binomial lattice matrices, when the unit price of non-renewable energy generation increases, a node moves straight to the right. Conversely, when the unit price of non-renewable energy generation decreases, the node moves down and to the right. For example, setting the one specific volatility level as the average values of three volatility scenarios, 18.14%, the results of Figs. 10 and 11 indicated that investing in R&D until 2013 was optimal regardless of fluctuations in the unit cost of non-renewable energy generation. However, if unit costs continue to increases past 2014, then optimal results would be obtained by deploying R&D. Thereafter, our results indicated that it would be desirable to continue investing in R&D for wind power until

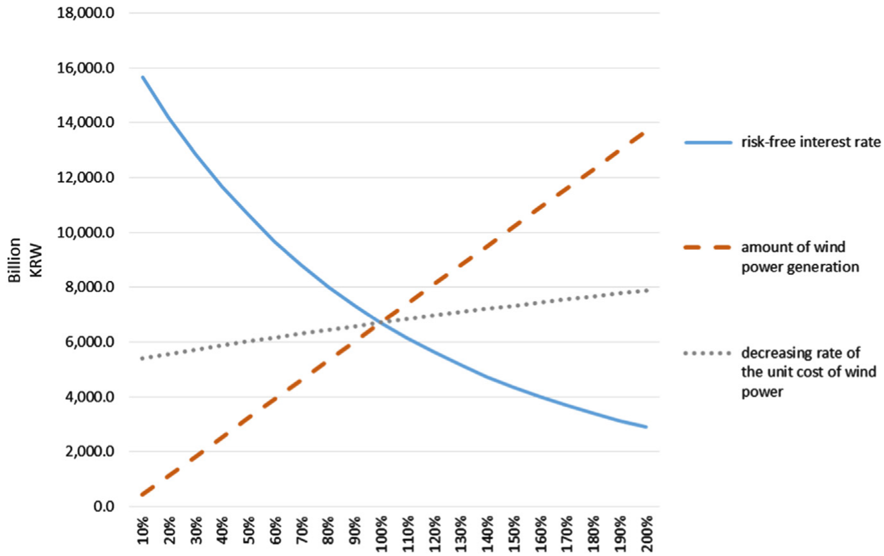

Fig. 12. Sensitivity analysis on NPV.

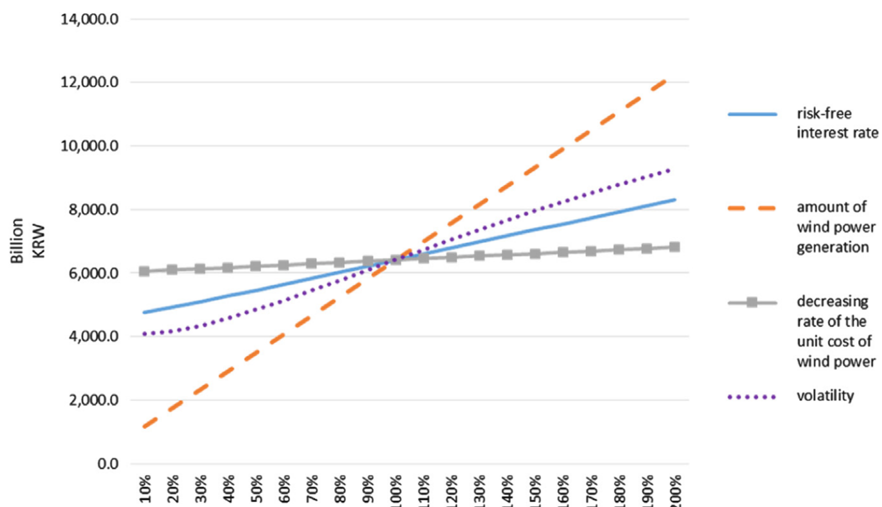

Fig. 13. Sensitivity analysis on ENPV with high volatility.

2018, even if the unit cost of non-renewable energy generation decreased. Meanwhile, if the unit cost of non-renewable energy generation follows a downtrend until 2019, a node at which abandonment was recommended appeared, indicating that the decision to further invest in wind power technology R&D must be reviewed. Furthermore, if the unit cost of non-renewable energy generation continues to decrease until 2022, all nodes appearing thereafter recommend abandonment, suggesting that it would no longer be optimal to invest in or deploy R&D of wind power energy.

In conclusion, investment in wind power R&D should continue until 2013 at the earliest. Starting from 2014, the industrial application of the wind power technologies resulting from R&D should be actively considered, because wind power energy has the possibility to be a highly competitive source of energy in Korea. Meanwhile, our results showed that if the unit cost of non-renewable energy generation decreases continuously until the year 2022, the most economically rational decision would be to abandon existing R&D projects. However, this case scenario is rather unrealistic, given that we are rapidly approaching the depletion of fossil fuels. Thus, a more sensible interpretation of the results of this study is that R&D in wind power energy should be continued.

Finally, under high volatility scenarios, the expanded NPV of wind power energy R&D stands at more than 6.42 trillion KRW. When compared to 6.71 trillion KRW and 5.73 trillion KRW, the static NPVs obtained using the DCF model, R&D is worth approximately −0.29 to 0.69 trillion KRW in total value. These results suggest that investment in wind power energy R&D makes significant economic sense, even when taking into consideration the future uncertainty regarding unit costs and the flexibility of decision-making.

4.4. Sensitivity analysis

In this study, we performed sensitivity analysis to examine the effects of the following parameters on NPV and ENPV: risk-free interest rate, volatility of unit costs of non-renewable energy, decreasing rate of the unit cost of wind power energy generation, and achievement rate of the goal of wind power generation. The base values for these parameters were 3.3% for the risk-free rate, volatility scenarios, 2% for rate of decrease, and 16,620 GWh for the goal of wind power generation. Figs. 12–15 show the results of sensitivity analysis, where the *X*-axis represents the percent changes in each parameter from the base value.

Based on the results of the sensitivity analysis, we found that the NPV would increase as decreasing rate of the unit cost of wind power and achievement rate of the goal of wind power generation increase, while the NPV would decrease as risk-free interest rate

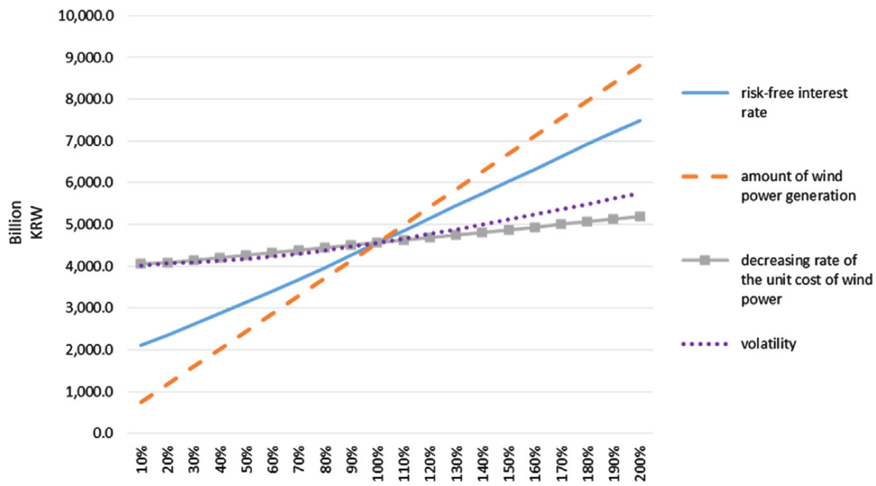

Fig. 14. Sensitivity analysis on ENPV with middle volatility.

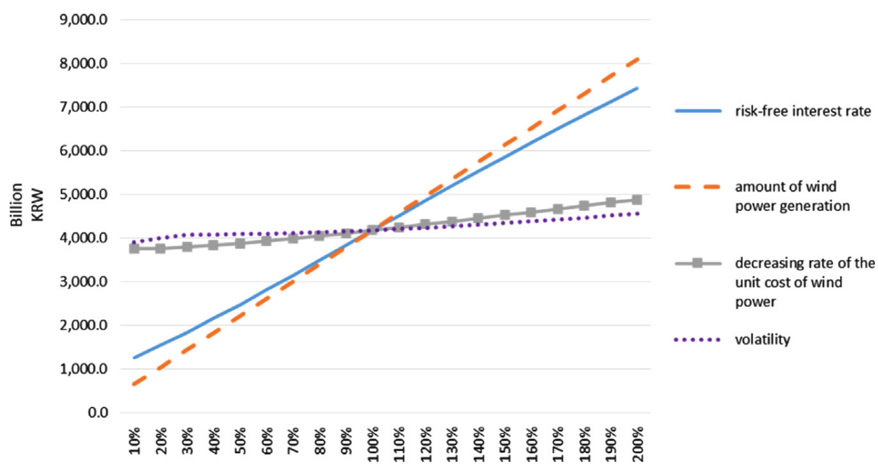

Fig. 15. Sensitivity analysis on ENPV with low volatility.

increases. On the other hand, it is found that the ENPV would increase as risk-free interest rate, the volatility of the unit cost of non-renewable energy, the decreasing rate of the unit cost of wind power energy generation and the achievement rate of the policy goal of wind power generation increase regardless of volatility scenario. In particular, ENPV was the most sensitive to changes in the rate at which the stated goal of wind power generation was achieved. Thus, the most critical factor in determining the economic value of wind power R&D was how much wind power energy could be utilized as a source of electricity generation. This finding implied that technological development as well as promotion of utilization of wind power is important for the Korean government to achieve economic viability of R&D investments in wind power energy.

5. Conclusions

The Korean government has recently implemented policies that emphasize new and renewable energy sources as a way to cope with the future global energy crisis due to depletion of fossil fuels and uncertainties in the energy market. In particular, by taking into consideration the geographical and climate environment of Korea, wind power has received a great deal of attention as the most economical source of renewable energy. Thus, there has already been considerable investment in R&D for wind power technology. However, there has been little effort made to quantitatively evaluate the reasonable economic value of renewable energy in Korea. Likewise, there has been publicity of negative results from an economic viewpoint due to the high initial investment costs of wind energy and skepticism regarding spontaneous market growth.

In this study, we empirically estimated the economic value of wind power energy R&D in Korea using both a traditional DCF valuation perspective and a real options analysis perspective. We found that wind power energy R&D is economically attractive in Korea, especially from the real option perspective when optimal deployment timing to respond to uncertain energy market was considered. The value of wind power energy R&D, including the value of managerial options, was estimated by taking into consideration the options available in an uncertain future environment, and was far greater than the NPV obtained from the DCF model under most scenarios, suggesting that R&D projects for wind energy represent a good investment.

Using the real option analysis results, we generated binomial lattices and used them to suggest optimal strategic decision-making paths with respect to situational changes in energy market uncertainty. Furthermore, using sensitivity analysis, we found that achieving the stated policy goal of the level of wind power generation was the most influential factor with respect to the economic value of wind power energy R&D. Based on these results obtained from this study, policies emphasizing not only technological development but also promotion of the utilization of wind power are important for the Korean government to succeed with developing wind power energy.

Future research should expand on this work and take into consideration additional factors, such as technological uncertainty related to the success of wind power energy R&D projects and the environmental impact of utilizing new energy technologies developed from R&D projects such as reduction in carbon dioxide emissions. And our analysis has a limitation that the path of wind power deployment was predetermined by assumption that Korean government's policy goal of deployment should be met by 2030, which is somewhat unrealistic. Thus it would be worthwhile to extend our research by treating the amount of wind power generation as a stochastic variable or a variable related to the decision made in R&D activities in some ways.

Acknowledgment

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